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GMRT observations of the field of INTEGRAL X-ray sources- II

(newly discovered hard X-ray sources)

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Abstract. We have conducted low-frequency radio observations with the Giant Metrewave Radio Telescope (GMRT) of 40 new hard X-ray sources discovered by the INTEGRAL satellite. This survey was conducted in order, to study radio emissions from these sources, to provide precise position and to identify new micro-quasar candidates. From our observations we find that 24 of the X-ray sources have radio candidates within the INTEGRAL error circle. Based on the radio morphology, variability and information available from different wavelengths, we categorize them as seventeen Galactic sources (4 unresolved, 7 extended, 6 extended sources in diffuse region) and seven extragalactic sources (2 unresolved, 5 extended). Detailed account for seventeen of these sources was presented in earlier paper. Based on the radio data for the remaining sources at 0.61 GHz, and the available information from NVSS, DSS, 2MASS and NED, we have identified possible radio counterparts for the hard X-ray sources. The three unresolved sources, viz IGR J17303−0601, IGR J17464−3213, and IGR J18406−0539 are discussed in detail. These sources have been identified as X-ray binaries with compact central engine and variable in X-ray and in the radio, and are most likely microquasar candidates. The remaining fourteen sources have extended radio morphology and are either diffuse Galactic regions or extragalactic in origin.

Key words. stars : X-ray binaries – X-ray : galaxies – X-ray : sources : INTEGRAL sources – Techniques : interferometry

1. Introduction

Many new hard X-ray emitting sources have been discovered during the deep Galactic plane survey by *INTEGRAL* satellite mission. The IBIS instrument has a point source location accuracy (PSLA) of typically $1 - 3'$ within a large field of view $29^\circ \times 29^\circ$ (Ubertini et al. 2003). 55 new hard X-ray sources have been reported in literature. A majority of these sources are believed to be Galactic X-ray binaries with a compact object orbiting a companion star (Bird et al. 2004). Some of these sources are identified as AGNs, radio galaxies, pulsars, CVs and dwarf nova. A detailed study of X-ray sources in the multi-wavelength band is essential to understand the emission mechanism and the accretion process on to the compact companion neutron stars (NS) or black holes (BH). The radio imaging of these sources can establish whether some of these are radio emitting X-ray binaries (REXBs) and show any microquasar like features. Due to their similarity with quasars, the jet feature in microquasars provide important information about the underlying physical phenomenon and the possible disk-jet connection which may power the observed emission in different wave bands. Their X-ray, infrared and radio properties can lead to classification schemes.

The detailed radio observations for these sources were made immediately after their discovery using the GMRT, to find the possible radio counterparts within the location error box of the X-ray source, to measure precise position if detected and to study the low frequency radio nature of the hard X-ray sources. The radio morphology of a source also provides its identification, viz Galactic, which are mainly compact (Becker et al. 1990) or extragalactic mostly extended (Jackson 1999). At meter wavelengths REXBs show point source morphology (Pandey et al. 2005a). We have also analyzed the available NVSS images at 1.4 GHz and other radio data in order to understand the radio spectrum of these sources. The archival data, from DSS, 2MASS and NED images is also used in our analysis to facilitate a complete study of these sources.

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Table 1. List of target INTEGRAL sources observed with GMRT

Source	Type	Integral Pos. Unc. 1.6σ	Variable 100s–1ks $\frac{\mathrm{IBIS}}{\mathrm{ISGRI}}$	X-ray Flux 15–40 keV (mCrab)	X-ray/optical/ UV/IR/Radio sources in X-ray error circ.	No.of sources in the X-ray error circ.
IGR J00370+6122	HMXB[1,2]	$2'$	Yes	-	BD+6073	
IGR J01363+6610	HMXB[2]	$2'$	Yes	17	HD9603	
IGR J16167−4957	-	$6''$	-	2	-	
IGR J16195−4945	HMXB(?)[*,10]	$16''$	-	-	HD146628	
IGR J16207−5129	-	$2'$	-	-	HD146803	
IGR J16358−4726	LMXB(?)[3,4] Pulsar[5]	$0.6''$	Yes	20-50 4.63	2MASS J163553−472539	
IGR J16393−4643	HMXB(?) Pulsar[5,6,7,11]	$2'$	Yes	3		20[**]
IGR J16558−5203	-	$8''$	-	-	1RXS J165605−520345 USNO-B1.0 0379−00008129	
IGR J17195−4100	-	$8''$	Yes	-	1RXS J171935−410054 USNO-B1.0 0489−00511283	
IGR J17200−3116	-	$9''$	Yes	-	1RXS J172006−311702	
IGR J17252−3616	HMXB[8] Pulsar	$2'$	-	-	IRAS 17220−3615 NVSS J172510−361614 HD319824	
IGR J17254−3257	-	$14''$	-	-	1RXS J172525−325717 USNO-B1.0 0570−00727635	
IGR J17285−2922	XB[9]	$2'$	Yes	-	IRAS 17252−2922 [T66b]320	
IGR J17303−0601	LMXB	$7''$	Yes	-	H1726−058 USNO−A2.0 0825−10606993 1RXS J173021.5−055933	
IGR J17456−2901	-	$1'$	-	-	1LC G359.923−00.013	90[**]
IGR J17460−3047	-	$2'$	-	-		80 IR sources[**]
IGR J17464−3213	BHC[*] LMXB[3]	$0.5'$	Yes	60	H1743−322 2MASS 17461525-3213542 USNO-A2.0 0525-294112269	
IGR J17475−2822	Sgr B2[5]	2–$3'$	-	-		200 [**]
IGR J17488−3253	-	$12''$	Yes	-	1RXS J174854.7−325444	
IGR J18027−2016	Pulsar[6]	$1'$	-	4.06	HD312525 1LC G000.683−0.035 IRAS 17594−2021	
IGR J18406−0539	-	2–$3'$	-	-	IRAS 18379−0546 AX J1840.4−0537 NVSS J184037−054317 GSC2.2	
IGR J18450−0435	-	2–$3'$	-	-	IRAS 18422−0437 PMN J1845−0433	
IGR J18490−0000	-	2–$3'$	-	-	-	

[1]High mass X-ray binary[1], Reig et al. 2005[2], Bird et al. 2004[3], Low mass X-ray binary[4], Revnivtsev et al. 2004[5], Lutovinov et al. 2005[6],Boudaghee et al. 2005[7], Zurita et al. 2005[8], X-ray binary[9], Sidoli et al. 2005[10], Soldi et al. 2005[11] http://isdc.unige.ch∼rodrigue/html/igrsources.html[*], [**] field sources identified at different wavelengths

2. Observations and Analysis

The radio observations were carried out at 0.61 GHz with bandwidths of 16 and 32 MHz respectively using the GMRT. The full array synthesized beam of the GMRT antenna at 0.61 GHz is $\sim 5'$.

As described in paper-I (Pandey et al. 2005b), the association of the possible radio counterpart to the *INTEGRAL* source was based on the observed radio morphology, flux density variability and cross-correlation with the NED catalogue. During the observations in the Galactic center region at low radio frequencies, the gain decrease due to system temperature becomes significant, hence system temperature corrections were applied to the flux densities of the radio measurements. The flux density

scale was set by observing the primary calibrators 3C286, 3C147 and 3C48. The phase calibrators were observed near the target source for ~ 5 min scan interleaved with 25 min scans on *INTEGRAL* sources. The data recorded from GMRT was converted into FITS files and analyzed using Astronomical Image Processing System (AIPS). The details of observation and analysis procedure are desribed in detail in paper-I.

During our observations, radio sources were detected in the field of sixteen hard X-ray sources and a possible radio counterpart for the seventeenth source been detected during VLA observations. All the possible seventeen radio counterparts of the twenty three hard X-ray sources are reported in this paper and for remaining sources no possible radio counterpart was detected within the 3σ position error circle of the X-ray source. In Table 1, we have listed physical properties of the sources observed during our survey along with the other available data, inferred class of the object and the field sources in other wave bands within the *INTEGRAL* error circle. A summary of the results of GMRT observations is given in Table 2. The best-fit radio positions for the counterpart and the position offset with respect to the X-ray position is given in column 7. Column 4 gives the radio flux density for the point (peak) and extended (total) sources. The rms noise given in column 5 of the table corresponds to the average background noise in the image field and is higher in the Galactic plane. In the radio images presented below, the bold ellipse marked with 'A' indicates the radio counterpart close to the X-ray source. We have grouped sources based on their radio morphology into point and extended sources. We discuss in detail some of these sources with genuine radio – X-ray association.

3. Results

3.1. Point radio sources within the field of INTEGRAL sources:

1- IGR J17303−0601 : This source was detected in the Norma arm region (Walter et al. 2004) and in coincidence with the *ROSAT* source 1RXS J173021.5−055933 (Voges et al. 1999, Stephen et al. 2005). Two optical objects with $R \sim 15.5$ and $R \sim 18$ are found within the *ROSAT* error box of $7''$ in the Digitized Sky Survey (DSS) field (Monet et al. 2003, Stephen et al. 2005). Two near-infrared sources in the (2-MASS survey) are also coincident with the optical sources. The optical spectra of both these sources acquired with the Bologna Astronomical Observatory show features identical to other X-ray emitting objects (Masetti et al. 2004). The brighter source within the *ROSAT* error box was considered to be the optical counterpart to IGR J17303−0601. All the optical emission lines of this object are at red shift zero, indicating its Galactic origin. The presence of the He II line strongly indicates that this object is undergoing mass accretion onto a compact star (e.g. van Paradijs & McClintock 1995), thereby suggesting the X-ray source to be a low mass X-ray binary with IGR J17303−061 as the optical counterpart. The optical photometry of the source however, suggests the hard X-ray source to be an intermediate polar with a spin period of 128 s (Gansicke et al. 2005).

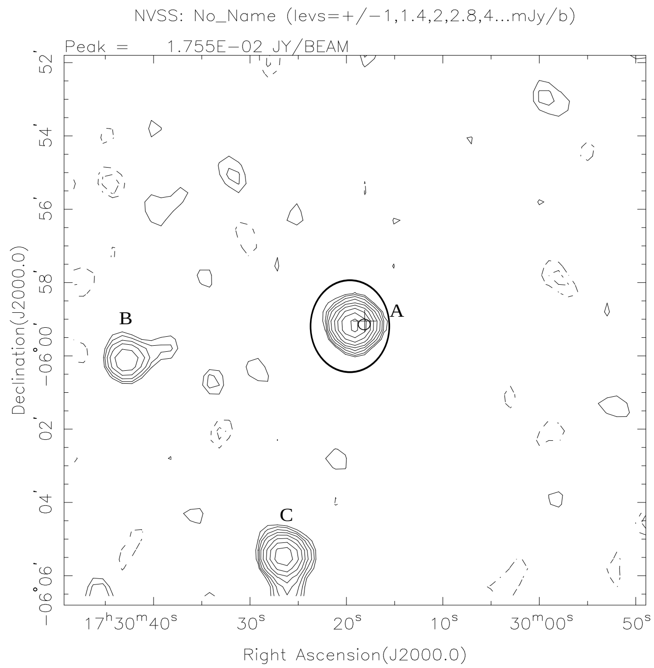

Fig. 1. NVSS image of IGR J17303−0601 at 1.4 GHz with the *INTEGRAL* position marked with +. Source 'A' is coincident in position with IGR J17303−0601. Sources 'B' and 'C' are field sources. The circle shows the *INTEGRAL* uncertainty error circle of 3σ ($14''$)

Radio observations of the source were made using GMRT, with the aim of finding any possible radio counterpart within the location error box of the X-ray source however no flux was detected from the source as seen in Table I. We then analysed the NVSS observations or the region conducted at 1.4 GHz with the VLA (Condon et al. 1998) and the radio image of the field is shown in Fig. 1. A compact point source 'A' of $\sim$18 mJy at 1.4 GHz is detected coincident with the *INTEGRAL* and *ROSAT* source position. The precise position with the radio observations is RA: 17h 30m 21.50s and DEC: −05d 59′ 33.5″ (J2000). Two other compact field sources 'B' with radio flux density $\sim$5 mJy and RA: 17h 30m 45.48 and DEC: −06d 01′ 57.17″ and 'C' with radio flux density $\sim$16 mJy and RA: 17h 30m 28.41 and DEC: −06d 05′ 56.27″, were clearly detected within the field and lie outside the *INTEGRAL* error circle. In order to search for the radio source at lower frequencies GMRT observations on this source was performed at 0.61 GHz. No radio source was found coincident in position with the NVSS source 'A' during our observations at 0.61 GHz. Fig.1 shows the NVSS field image of the source IGR J17303−0601. The 3σ upper limit in the GMRT image was $\sim$6 mJy and the rms noise was $\sim$1.84 mJy beam^{-1}. The sources 'B' and 'C' with

radio flux density ∼18 mJy and ∼15.5 mJy were clearly detected coincident in position with the NVSS sources.

At radio wavelengths the detection at 1.4 GHz and non-detection at 0.61 GHz with positive detection of other field sources suggest that IGR J17303−0601 is a radio emitting X-ray binary (REXB). And the source is highly variable or absorbed at low frequencies. The absorption may be due to synchrotron self absorption process dominant at low frequencies as seen for most of the X-ray binaries (Pandey et al. 2004). In both the cases, a non-thermal origin of the radio emission is favored. Like few other sources in the Norma Arm region even this source was highly absorbed at low frequencies (Pandey et al. 2005b).

2- IGR J17464−3213 : This transient BH candidate was detected by the *INTEGRAL* satellite on 21st March, 2003 (Revnivtsev et al. 2003). The position of the source is consistent with the position of the HEAO source H1743−322 (Markwardt & Swank 2003, Gursky et al. 1978). The spectral fit to the JEM-X/IBIS data shows the presence of a soft component fitted by a multi color disk black body and a hard power-law tail with photon index of 2.2 which extends to 80 keV. The observations made during the outburst shows that the light curve is typical of a X-ray nova (Steeghs et al. 2003). It is therefore believed that IGR J17464−3213 is a classical X-ray nova – a LMXB harboring a BH – which experienced a recurrent outburst in 2003 (Lutovinov et al. 2005).

The RXTE pointed observations on 28th Mar, 2003 gave mean fluxes 50, 200 and 220 mCrab in 2 – 10, 15 – 40 and 40 – 100 keV range respectively. A strong quasi periodic oscillation (QPO) with the period ∼ 20 s was also seen in the X-ray light curve. The X-ray spectrum is consistent with an absorbed power law with photon index 1.49±0.01 and an absorption column of 2.4×10^{22} cm^{-2}. Compton reflection signatures are seen in the continuum spectrum (Grebenev et al. 2003, Capitanio et al. 2005). The RXTE monitoring of the source between May – July, 2004 observed IGR J17464−3213 in several BH states and revealed various types of variability, including QPOs of 7.8 Hz (Homan et al. 2005).

During the follow up observations with the VLA on 30th, March and 1st April, 2003 a compact, variable source was detected at 4.8 GHz at, RA: 17h 46m 15.61 ± 0.01s, DEC: −32d 13′ 59.9 ± 1.0″ (J2000) and approximately 0.64′ from the original *INTEGRAL* position. It is consistent with the position of H1743−322 (Swank et al. 2004). The source flux was 4 mJy on 30th March, and had brightened by about 50% on 1 April. A strong radio flare was detected on 8th April, 2003 (Rupen et al. 2003a). The ATCA radio observations of H1743−322 performed from Nov, 2003 – June, 2004 led to the discovery of large-scale radio jets on each side of the BHC H1743−322 (Corbel et al. 2005).

The optical observations in the *I*-filter at the radio position show a marginal detection of an optical counterpart

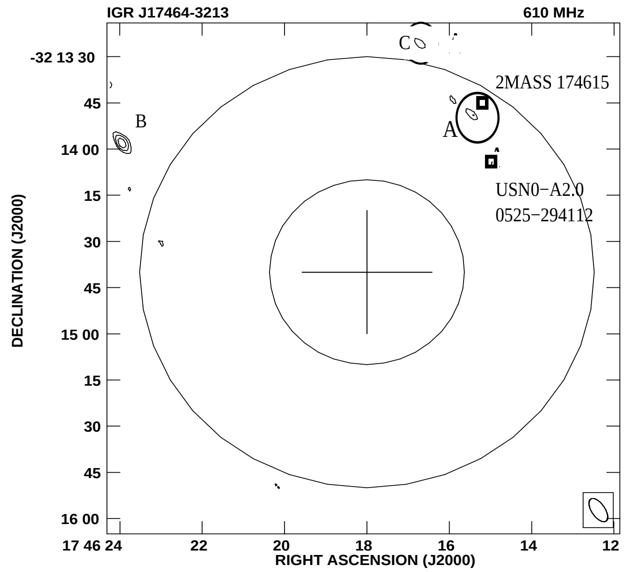

Fig. 2. GMRT image of IGR J17464−3213 at 0.61 GHz with the *INTEGRAL* position marked with + . The small and large circles shows the *INTEGRAL* uncertainty error circles of 1.6σ and 3σ. The contour levels are 2 mJy × 1, 1.4, 2. The field sources 2MASS 17461525-3213542 and USNO-A2.0 0525-294112269 are marked in the figure.

at a level of $I_{mag} \sim 20$ (Khamitov et al. 2003, Remillard et al. 2003, Steeghs et al. 2003, Rupen et al. 2003b).

On 3rd Jul, 2004 a second outburst was detected in the X-ray light curve of IGR J17464−3213 and it went into hard X-ray state (Swank et al. 2004). During the end of the X-ray state, the radio source was not detected at the position mentioned by (Rupen et al. 2003a) until 4th Aug 2004 during VLA observations at 4.86 GHz; however, it was positively detected by VLA on 5th Aug 2004, with a flux density of 1.96±0.15 mJy (Rupen et al. 2004). During GMRT observations on 25th July, 2004, a radio source was detected coincident with the VLA position reported by Rupen et al. 2003a, at a radio flux density of 2.75±0.52 mJy refer Fig. 2. It is also interesting to note that two compact sources, (B) of flux level 6 mJy at position coordinates, RA: 17h 46m 24.17s and DEC: −32d 13′ 59.92″ and (C) of flux level 2 mJy at position coordinates, RA: 17h 46m 16.55s and DEC: −32d 13′ 29.89″ are also detected within the field of IGR J17464−3213; however, they clearly lie outside the *INTEGRAL* position error circle. The analysis of the NVSS data at 1.4 GHz shows no point sources coincident with the radio sources (A) and (B), detected by the GMRT; however, the source (C) was positively detected in the NVSS field at a flux level of ∼1.05 mJy. There were no other radio observations reported at this epoch. Hence two variable radio sources (A, B) are detected witin the field of *INTEGRAL* source; however, the source (A) is most likely to be associated

with the hard X-ray source and it clearly shows transient behavior at radio wavelengths like other LMXBs.

In order to determine IR and optical counterparts, we have analysed the 2MASS and USNO data near the radio source (A) position for the field of IGR J17464−3213. An IR point source, 2MASS 17461525-3213542 with coordinates RA: 17h 46m 15.25s and DEC: −32d 13′ 54.2″ and magnitudes, $J = 16.2, H = 13.8, K = 13.16$ and an optical source, USNO−A2.0 0525−294112269 with position coordinates RA: 17h 46m 14.77s and DEC: −32d 14′ 06.02″ and magnitudes, $B = 19.6, R = 17.4$ lies within the error circle of the hard X-ray source and close to the radio source (Voges et al. 2004). Thus H1743−322, 2MASS 17461525-3213542, and USNO−A2.0 0525−294112269, may be most likely associated with IGR J17464−3213.

Thus possible counterparts in IR and optical wavelengths and a variable radio counterpart for the source IGR J17464−3213 has been detected, which confirms that IGR J17464−3213 is a REXB and a microquasar candidate. However, it is necessary to perform simulataneous radio observations during the flaring episodes to understand the system in detail.

3- IGR J18406−0539 : The source was discovered during the observations of the Sagittarius arm region by IBIS telescope during the spring of 2003 (Belanger et al. 2004). We have carried out cross identification of this source with the data available from various catalogues, to identify the nature of the source. A hard X-ray source, AX J1840.4−0537 discovered during ASCA observations with RA: 18h 40m 24s and DEC: −05d 37′ 00″ lies within the position error circle of the source (Bamba et al. 2003). The field is further complicated by the presence of an optical source, GSC2.2 with magnitudes $B = 16$ and $R = 19$ and position RA: 18h 40m 38.094s and DEC: −05d 43′ 19.30″ lying within error circle (Monet et al. 1998). Fig. 3 shows the radio image of the field of IGR J18406−0539 at 0.61 GHz with the other known field sources .

An IR point source, 1RAS J18379−0546 (Cutri et al. 2003), with coordinates RA: 18h 40m 38.04s, DEC: −05d 43′ 20″ and magnitudes $J = 12.89, H = 11.91, K = 11.61$, also lies within the 2σ position error ellipse of the hard X-ray source. Thus the sources AX J1840.4−0537, GSC2.2 and 1RAS J18379−0546 are therefore, likely associated with the counterparts of IGR J18406−0539.

During GMRT observations a point source was detected with radio flux density of $\sim$ 28 mJy and at RA: 18h 40m 37.61s and DEC: −05d 43′ 17.99″, which is 4.31′ away from the hard X-ray source. The NVSS image of the field also shows a point source of 165 mJy coincident with the GMRT position. Using the various radio survey, we have computed the radio spectrum for the source (non-simultaneous measurement) in Fig. 4. It can be seen from the figure that the spectrum is highly inverted at meter wavelengths. It is interesting to note that the NVSS survey at 1.4 GHz and the Galactic Plane Radio-source Survey at 1.4 GHz (Zoonematkermani et al. 1990) for the compact Galactic source at different epochs gave the radio flux density of 165 mJy and 80 mJy respectively. A variability in the radio flux density by a factor of two is clearly measured. The Galactic plane survey at 4.87 GHz by (Altenhoff et al. 1979) gave the radio flux density for the source as 200 mJy. This information implies that the

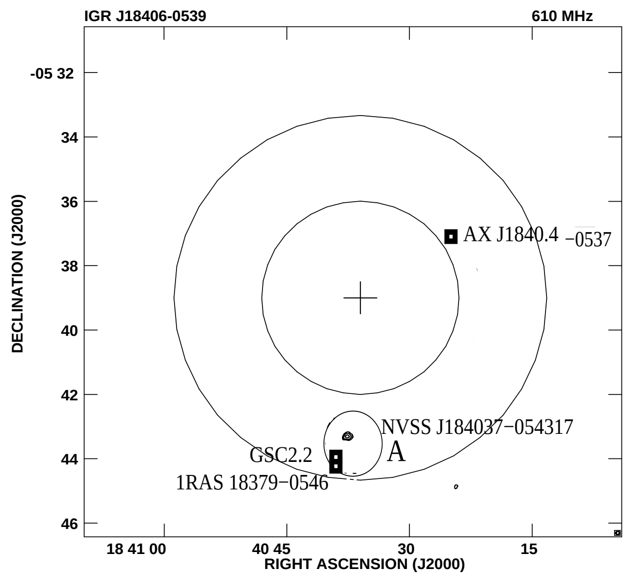

Fig. 3. GMRT image of IGR J18406−0539 at 0.61 GHz with the *INTEGRAL* position marked with + . The small and large circles shows the *INTEGRAL* uncertainty error circles of 1.6σ and 3σ. The contour levels are 5.5 mJy × 1, 2, 4, 8. The boxes show the ASCA, optical and IR sources within the *INTEGRAL* error circle. The field sources AX J1840.4−0537, 1RAS 18379−0546, NVSS J184037−054317 and GSC2.2 are marked in the figure.

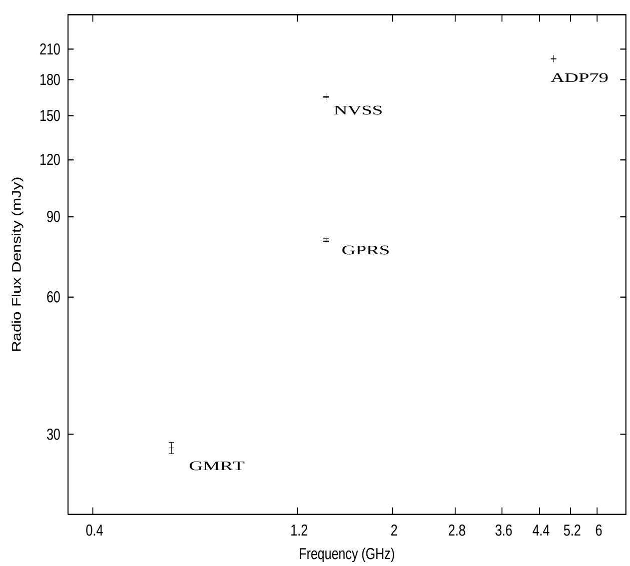

Fig. 4. Radio spectrum for IGR J18406−0539

source shows absorption at lower frequencies and is variable in nature. It is important to do further observations in the optical and infrared band to confirm the nature of the companion star. However, from the available information we infer that the source IGR J18406−0539 is most likely a REXB, transient in nature and a possible microquasar candidate.

3.2. Extended radio sources within the field of INTEGRAL *sources:*

3.2.1. Extragalactic radio sources within the field of *INTEGRAL* sources:

The Galactic binary X-ray sources are mostly unresolved at arcsec scale (Pandey et al. 2005a). The extended sources can thus be catagorized as extragalactic in nature. From our GMRT observations, we find that **among the remaining twenty sources,** the radio emission observed in the direction of three sources, viz, IGR J17195−4100, IGR J17200−3116 and IGR J17456−2901 is extended in nature and having a double source morphology, which is typical of the extragalactic sources. Hence, we classify these as extragalactic radio sources. In Fig. 5, we have plotted the GMRT image of IGR17195-4100 taken at 0.61 MHz. The data clearly suggests the sources to be a a radio galaxy. The cross identification with the NED catalogue (Voges et al. 1999, Condon et al. 1982, Pappa et al. 2001) also confirms their extragalactic nature of both these regions. In regards to the true association of the radio source with the hard X-ray source, it is quite likely that the X-ray sources are indeed extragalactic. No X-ray spectral data is yet available to infer the galactic origin of the source. However, if the X-ray sources are galactic in origin, then the observed radio association will be a case of fortutious line of sight coincidence. we have listed the known field sources within the *INTEGRAL* error circle in Table 1. The optical counter part for IGR J17195−4100 in the table is listed from USNO catalogue.

3.2.2. Extended Galactic radio sources in diffuse region within the field of *INTEGRAL* sources:

Among the rest seventeen sources, eleven hard X-ray sources do show extended radio morphology within the position error circle. The available X-ray spectra on of few of these sources suggest their binary nature and galactic origin (refer table 1). No known extragalactic radio sources from the NED catalogue lie in the position error circle of these *INTEGRAL* sources and in coincidence with GMRT position. The observed radio emission with morphology non similar to the radio galaxies and with no known extragalactic identification therefore suggests that these extended sources may most probably be associated with the radio emitting regions within the galaxy. From the GMRT data, based on their radio morphology, the eleven *INTEGRAL* hard X-ray sources can be grouped in two classes; (a) extended Galactic source and (b) extended

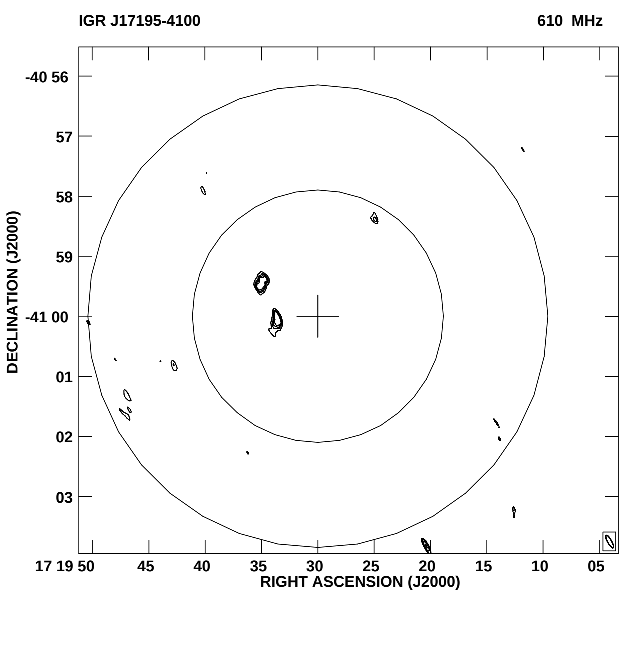

Fig. 5. GMRT image of IGR J17195−4100 at 0.61 GHz with the *INTEGRAL* position marked with + . The small and large circles shows the *INTEGRAL* uncertainty error circles of 1.6σ and 3σ. The countour levels are 2.3 mJy × 1.0, 1.2, 1.3, 1.4, 2.0, 2.8, 4.0, 8.0, 16.0, 32.0

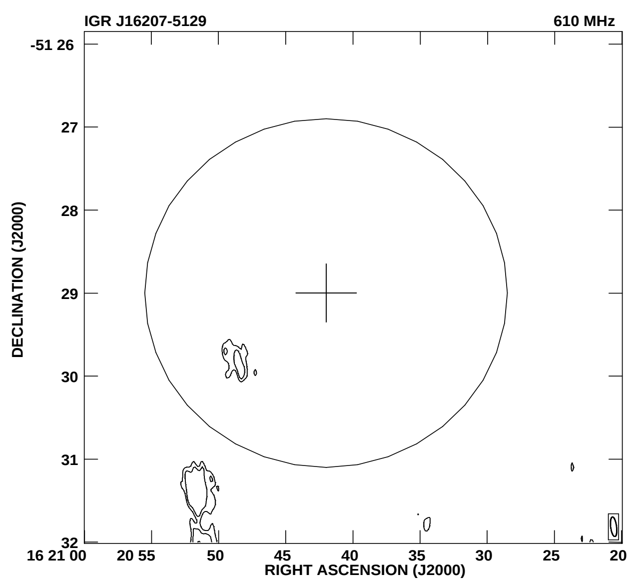

Fig. 6. GMRT image of IGR J16207−5129 at 0.61 GHz with the *INTEGRAL* position marked with + . The circle shows the *INTEGRAL* uncertainty error circle of 1.6σ. The countour levels are 3.0 mJy × 1.0, 1.2, 2.0, 2.8, 4.0, 8.0, 16.0, 32.0.

source typical of the diffuse emission regions. In the Fig.

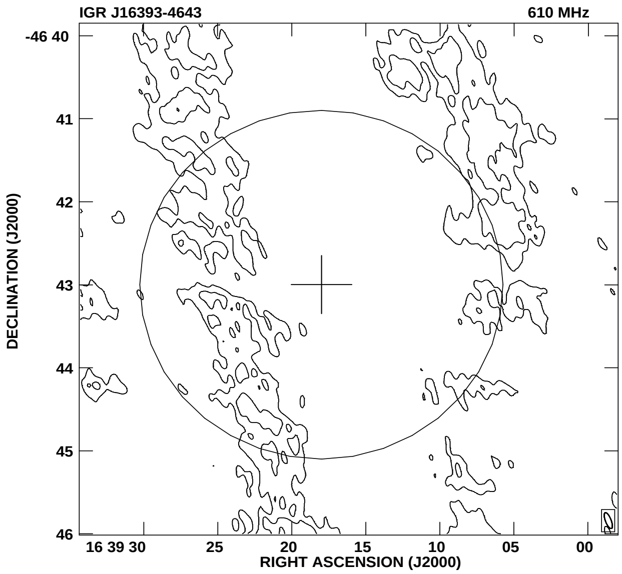

Fig. 7. GMRT image of IGR J16393−4643 at 0.61 GHz with the *INTEGRAL* position marked with + . The circle shows the *INTEGRAL* uncertainty error circle of 1.6σ. The countour levels are 2.0 mJy × 1, 2, 4, 18, 16, 32, 64

6 and 7 we have plotted representative radio images for the two groups. The image shown in figure 6 is similar to the one having an extended jet emission while figure 7 is reminscent of the molecular clouds.

Five hard X-ray sources, namely, IGR J16207−5129, IGR J16558−5203, IGR J17285−2922, IGR J17460−3047 and IGR J18450−0435 belongs to group (a). Except IGR J17285-2922, all sources are located in the Norma Arm region and have high probability of being galactic in nature. The X-ray spectrum of IGR J17285−2922 shows XB characteristics (Barlow et al. 2004); however, the nature of remaining sources is not yet identified. Positive detection of extended radio emission at low frequencies, associated with the galactic X-ray sources seen in the GMRT data suggests the presence of a new class of galactic extended radio sources.

Six sources, viz IGR J16167−4957, IGR J16195−4945, IGR J16393−4643, IGR J17252−3616, IGR J17254−3257, and IGR J17475−2822 belongs to group (b). Except IGR J17285−2922, all the sources in this group were detected in the Norma Arm region **(refer table 1)**.

As seen from Fig. 7, due to the large extent of the radio emission, it is difficult to associate a single region with the X-ray source, even though the radio emission lies within the position error circle of the X-ray source. The sources IGR J16393−4643, IGR J17456−2901, IGR J17460−3047 and IGR J17475−2822 have crowded fields with large number of field sources >20, as expected from the diffuse regions. Therefore, we conclude none of these radio sources may be associated with the *INTEGRAL* sources.

3.3. X-ray sources with no radio counterpart

Six sources viz, IGR J00370+6122, IGR J01363+6610, IGR J16358−4726, IGR J17488−3253, IGR J18027−2016 and IGR J18490−0000 have no GMRT counterpart. It has been suggested that IGR J00370+6122 and IGR J01363+6610 are HMXB systems (Reig et al. 2005). Hence either these sources are not REXBs or these are synchrotron self absorbed at low frequencies at which our observations were made or these are highly variable in radio band. Follow up observations in the radio window is necessary to confirm the variable nature of these sources.

4. Summary and Conclusion

We have presented the radio analysis of 23 of the newly discovered *INTEGRAL* hard X-ray sources. Most of these sources are X-ray binaries; however, the identification of AGNs, radio galaxies, X-ray novas, CVs and pulsars are the other important byproducts. Among the twenty three sources observed, seventeen have a possible radio counterpart detected at radio wavelengths. The position offset of the possible radio counterparts with respect to the *INTEGRAL* position is of the order of few arc minutes. The consistent position provided by the GMRT will allow the search for infrared/optical counterparts for these sources to be detected. Based on the radio morphology of these source we have further grouped them into:
(a) Galactic point source,
(b) extended Galactic sources and sources in diffuse Galactic emission,
(c) extragalactic sources.
Three sources belong to group (a) and are REXBs. We carried out a detailed study of these three sources and their possible counterparts at other wavebands. Based on the variability in the radio and X-ray windows along with the information available about the counterparts in other wavebands we infer that IGR J17303−0601, IGR J17464−3213 and IGR J18406−0539 are possible microquasar candidates. However, devoted radio observations are necessary to confirm the jet emission from these sources. We have also detected a variable compact radio source within the field of IGR J17464−3213. Eleven sources can be associated with group (b), the diffused Galactic region, and three sources satisfy the radio morphology of extragalactic sources, group (c). No radio counterpart was detected for the remaining sources.

To conclude, we highlight that our observations were very important in pinpointing the possible microquasar candidates from the list of 40 *INTEGRAL* sources observed at radio wavelength. We have performed repeated observations on these sources of our interest in Cycle 7 to look for the radio variability and the data has to be analyzed.

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Table 2. Possible Radio counterparts of target INTEGRAL sources observed with GMRT at 0.61 GHz

Source	Date dd/mm/yy	S_ν (Peak/Total) (mJy)	σ (mJy b^{-1})	Radio Pos. GMRT RA & DEC	Pos. Off. w.r.t Integral Pos.	Radio Structure GMRT	S_ν(NVSS) (Peak/Total) (mJy)
IGR J00370+6122	25/06/04	≤7.00	2.18	-	-	-	≤1.6
IGR J01363+6610	25/06/04	≤7.00	2.31	-	-	-	2.5(E)
IGR J16167−4957	23/07/04	725	2.90	16h 16m 44.29s±0.91 -49d 57′ 10.02″±0.71	0.12′	Extended (DG)	N/A
IGR J16195−4945	30/07/04	256.4	0.84	16h 19m 35.07s±0.21 -49d 44′ 59.01″±0.28	0.84′	Extended (DG)	N/A
IGR J16207−5129	30/07/04	60.50	0.78	16h 20m 48.54s±0.77 -51d 29′ 50.01″±0.98	1.33′	Extended (DG)	N/A
IGR J16358−4726	31/07/04	≤7.50	2.5	-	-	-	N/A
IGR J16393−4643	23/07/04	79.25	1.63	16h 39m 03.9s±0.51 -46d 42′ 15.55″±0.59	2.58′	Extended (DG)	N/A
IGR J16558−5203	30/07/04	27.24	0.78	16h 55m 46s±0.04 -52d 03′ 58″±1.04	0.69′	Extended (E)	N/A
IGR J17195−4100	23/07/04	33.44	0.56	17h 19m 34s±0.22 -41d 00′ 00″±1.24	0.98′	Extended (DS-E)	N/A
IGR J17200−3116	23/07/04	33.03	0.51	17h 19m 55s±0.74 -31d 16′ 01″±0.70	0.55′	Extended (DS-E)	20 (E)
IGR J17252−3616	25/07/04	36.74	1.88	17h 25m 11.09s±1.71 -36d 16′ 48.01″±0.20	0.82′	Extended (DG)	700 (E)
IGR J17254−3257	25/07/04	359.65	0.43	17h 25m 24s±1.22 -32d 55′ 10″±1.33	3.12′	Extended (DG)	≤2.5
IGR J17285−2922	25/07/04	74.88	0.59	17h 28m 28.75s±0.07 -29d 21′ 04.51″±1.24	0.96′	Extended (E)	≤2.7
IGR J17303−0601	25/06/04	≤6.00	1.84	-	-	-	18 (P)
IGR J17456−2901	23/07/04	23.11	1.53	17h 45m 38.07s±0.04 -29d 00′ 40.00″±1.87	0.56′	Extended (DS-E)	17200 (E)
IGR J17460−3047	30/07/04	2.50	0.46	17h 45m 59.69s±0.03 -30d 46′ 58.00″±2.33	0.076′	Extended (E)	≤2.3
IGR J17464−3213	25/07/04	2.75±0.52	0.50	17h 46m 15.61s±0.28 -32d 13′ 59.9″±0.21	0.64′	Point	≤2.4
IGR J17475−2822	23/07/04	12.50	1.27	17h 47m 25.68s±0.62 -28d 22′ 21.96″±1.21	1.02′	Extended (DG)	1920 (E)
IGR J17488−3253	30/07/04	≤2.10	0.67	-	-	-	≤1.6
IGR J18027−2016	25/06/04	≤7.00	2.32	-	-	-	≤1.3
IGR J18406−0539	23/07/04	28.03±0.76	0.76	18h 40m 37.61s±0.12 -05d 43′ 17.99″±0.18	4.31′	Point	165 (P)
IGR J18450−0435	23/07/04	207.94	0.76	18h 45m 12.05s±1.06 -04d 40′ 05.99″±1.69	5.90′	Extended (E)	74 (E) ≤1.4
IGR J18490−0000	23/07/04	≤3.5	1.25	-	-	-	

[2] DS-E: Double Source Extragalactic, E: Extended, P: Point, DG: Diffused Galactic Region